Water Science and Engineering 2017, 10(2): 97–106

Available online at www.sciencedirect.com

Water Science and Engineering

journal homepage: http://www.waterjournal.cn

Experimental study and modeling of hydromechanical behavior of concrete fracture

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Received 2 January 2017; accepted 23 March 2017
Available online 13 June 2017

Abstract

In this study, the hydromechanical behavior of a concrete fracture under coupled compressive and shear stresses was investigated. A special experimental device was designed to create a planar fracture in a cylindrical sample and to carry out different kinds of hydromechanical tests on the fracture. Four series of laboratory tests were performed on an ordinary concrete sample. Hydrostatic compression tests were first conducted to characterize the normal compressibility of the fracture. In the second series, direct shear tests were conducted on the fracture under different normal stresses. The maximal shear stress of the fracture was determined as a function of the normal stress. In the third series, fluid flow tests were carried out in view of characterizing the overall hydraulic conductivity of the fracture as a function of its opening and closure. Shear tests with a constant fluid pressure were finally performed to investigate the influence of fluid pressure on the deformation behavior of concrete fractures. Based on the experimental investigation, an elastoplastic model is proposed. This model takes into account the nonlinear elastic behavior of a fracture under normal compression and the plastic deformation and failure due to shear stress. The model was coupled with the classical Darcy's law to describe the fluid flow along the fracture by considering the variation of permeability with fracture aperture. Numerical results agree with experimental data from various laboratory tests.

Keywords: Concrete fracture; Direct shear; Hydromechanical coupling; Hydraulic conductivity; Elastoplastic model

1. Introduction

Concrete is widely used in different engineering fields, including hydraulic constructions. In many cases, concrete materials are subjected to mechanical and hydraulic solicitations as well as chemical degradation. Among various aspects related to the performance of concrete structures, the damage induced by microcracks is an essential process of inelastic deformation and failure of concrete materials. In many cases, the failure of concrete structures is induced by the coalescence of microcracks, leading to localized macroscopic fractures. The description of the transition from diffused damage to localized fracture remains so far the most important challenge of durability analysis of concrete structures. A great number of experimental studies have been performed on mechanical and transport properties of various types of concrete in relation to damage evolution. It has been found that microcrack-induced damage affects not only mechanical behaviors but also transport and diffusion properties. The main consequences include deterioration of elastic properties, induced anisotropy, unilateral effects, friction-damage coupling, irreversible deformation and hysteretic response, and significant modification of permeability and thermal conductivity (Kermani, 1991; Sugiyama et al., 1996; Wang et al., 1997; Abbas et al., 1999; Baroghel-Bouny et al., 1999; Picandet et al., 2001; Choinska et al., 2007; Hoseini et al., 2009; Yurtdas et al.,

This work was supported by the National Key Basic Research Program of China (Grant No. 2006CB400502), the French National Agency for Radioactive Waste Management (Grant No. 51992), and the European Commission through the Collaborative Project Cebama (Grant No. 662147).
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Peer review under responsibility of Hohai University.

http://dx.doi.org/10.1016/j.wse.2017.06.002

2011). These studies have clearly shown an inherent relationship between concrete permeability evolution and microcrack growth. However, most existing works are so far limited to concrete materials with diffused microcracks or without fully connected localized cracks. There have been very few studies devoted to hydromechanical behaviors of individual concrete fractures, in particular when such fractures are subjected to both normal and shear stresses. Experimental data are obviously necessary for modeling progressive propagation of localized fractures, the key phenomenon of the failure process in concrete structures (Bourgeois et al., 2002; Chen et al., 2011). For this purpose, we intended to obtain more experimental data in this study. Original and quite comprehensive laboratory investigations are proposed in order to characterize both mechanical and hydraulic properties of concrete fractures in different loading conditions, and a fresh fracture in CEM I concrete was investigated. A specific homemade device was designed, allowing the creation of a planar fracture in a standard cylindrical sample (Shao, 2016). With this device, different kinds of laboratory tests were performed on the fracture: the hydrostatic compression test, direct shear test, and water flow test. The obtained results allow the characterization of elastic deformation, plastic deformation, failure properties, and permeability variation of the fracture.

Based on the experimental study, an elastoplastic model was formulated to describe the mechanical behavior of the concrete fracture. The formulation of the model is based on previous works performed on rock joints. For instance, Bandis (1980), Gentier (1986), Plesha (1987), Bart (2000), Barton et al. (1985), Yeo et al. (1998), and Misra (2002) proposed various constitutive models for rock joints under normal compressive and shear stresses. On the other hand, a number of studies have been performed to investigate hydraulic properties through a single fracture or joint (Tsang and Witherspoon, 1981, 1983; Moreno et al., 1990; Olsson and Brown, 1993). The present model describes the nonlinear elastic behavior of the fracture under normal compressive stress and the plastic deformation due to shear stress. The effect of fluid pressure on the fracture deformation was also investigated. Finally, using the classic Darcy's law and the mass balance equation, water flow along the concrete fracture was studied. Comparisons of numerical and experimental results are presented and discussed.

2. Material and experimental procedure

The studied material was a so-called CEM I concrete, which was chosen by ANDRA (the French National Agency for Radioactive Waste Management) for potential use in underground structures for nuclear waste disposal (Camps, 2008). This concrete is composed of cement (CPA, CEM I 52.5, PM, ES, and CP2), sand (washed limestone with a size of 0−4 mm), fine gravel (washed limestone with a size of 5−12.5 mm), adjuvant, and water. The water-cement ratio was 0.43, and the gravel-sand ratio was 1.1. The concrete was molded inside a coffering beam with a length of 56 cm and a section of 14 cm × 14 cm. After six months of maturation in lime water at a temperature of 20 °C, cylindrical samples were cored in water, and cut up and rectified to reach a desired size.

All laboratory tests were conducted using a self-designed autonomous triaxial system (Liu et al., 2015, 2016). This testing system was composed of a conventional triaxial cell, used to apply a confining stress (P_c) by injection of water into the cell chamber, an upper pressure chamber to generate an axial stress through the piston, and a circuit for an interstitial fluid flow. This testing system was also equipped with a compensation chamber inside the upper part of the cell. The liquid used to generate the confining stress was connected to this chamber. Therefore, the application of confining stress would not generate any force on the piston of the cell. The axial stress applied on the piston by the upper pressure chamber would generate a pure deviatoric stress. The axial stress and confining stress were both applied and monitored by an independent pressure generator. The axial strain was measured by two LVDT sensors, while the radial strain was measured by a self-designed circumferential strain ring. All monitoring data were collected in an acquisition computer.

In order to create a planar fracture in a cylindrical sample and subsequently to carry out a direct shear test on the crated fracture, a new experimental device was designed. The principle of the device is illustrated in Fig. 1. This device is composed of two cylindrical shearing discs with the same diameter as the sample. Each disc consists of two semi-discs made of different materials (A and B) with different stiffness. The two semi-discs are placed in opposite positions at the top and bottom surfaces of the sample. Due to a large stiffness difference between the two semi-discs, an axial displacement generated by the cell piston creates a shear stress along the diameter plane of the sample, leading to a planar fracture, and then the shear stress (τ) is applied along the fracture. Note that a rotation force can be generated before the creation of a fracture due to the difference of forces applied to two semi-discs. After a series of preliminary tests, it was found that the effect of such a rotation force was very small, and no sample rotation was observed.

A narrow cylindrical sample was chosen. The diameter and height of the sample were 37 and 45 mm, respectively. The sample was placed between two composite discs and inside a plastic jacket. The creation of a fracture is always done under a confining stress, for instance 5 MPa, in order to prevent a

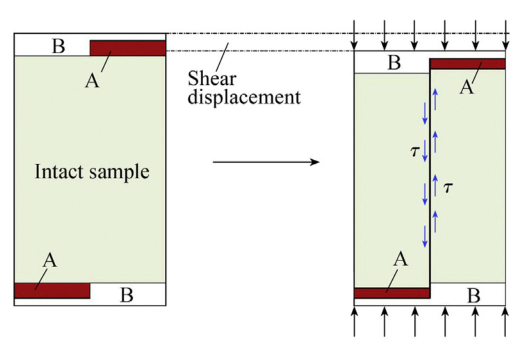

Fig. 1. Schematization of experimental device for creation of fractures and direct shear tests.